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REFLECTED OVERPRESSURE IMPULSE ON A
FINITE STRUCTURE

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December 1983



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The effect of angle of incidence of the shock front on reflected impulse loading on a finite structure is presented in this report. Impulse reflection factors have been developed for angles of incidence from zero to ninety degrees. Reflected impulse on a finite structure is much less than reflected impulse on an infinite plane because of the unloading due to rarefaction waves propagation from the sides of the structure which lowers the reflected overpressure.		

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I. INTRODUCTION

A. Background

During one of the meetings of the Blast Technology Subcommittee for the Revision of the Protective Structures Manual¹ it was pointed out that there was a data gap with regard to the effect of angle of incidence on reflected impulse impinging on finite structures. The effect of angle of incidence of the shock wave striking an infinite plane on peak reflected pressure and reflected impulse has been documented in many height of burst studies. The latest of these was conducted in Canada and reported in References 2 and 3. After a literature survey there appeared to be little information on the effect of angle of incidence on reflected impulse loading of isolated structures.

B. Objective

The objective of this study is to determine experimentally the effect of angle of incidence of the shock front on the reflected impulse loading on an isolated structure. The experiment was conducted with 1/50 scaled nonresponding models of a single structure.

II. TEST PROCEDURES

This section will describe the procedure followed in conducting an experimental program to meet the stated objective.

A. Design of Model

The model was designed to represent a structure 15.24 metres wide by 15.24 metres long by 22.86 metres high (50 ft x 50 ft x 75 ft). A 1/50th scale produced a model 0.305 m x 0.305 m x 0.457 m (1 ft x 1 ft x 1.5 ft). The model was constructed of a 2.54 cm thick steel plate. A sketch of the model is presented in Figure 1. The four upright walls were welded together with the top bolted on to allow access to the pressure gages. A reinforced concrete mount with an anchor bolt imbedded (as shown in Figure 2) was used to secure the model. The pressure transducers were then

¹ Department of the Army, the Navy, and the Air Force, "Structures to Resist the Effects of Accidental Explosions," June 1969, TM5-1300, NAVFAC P-397, AFM 88-22.

² R.E. Reisler, B. Pettit and L. Kennedy, "Air Blast Data from Height of Burst Studies in Canada, Vol I: HOB 5.4 to 71.9 Feet," BRL Report No. 1950, December 1976 (AD B016344L).

³ R.E. Reisler, B. Pettit and L. Kennedy, "Air Blast Data from Height of Burst Studies in Canada, Vol. II, HOB 4.5 to 144.5 Feet," BRL Report No. 1990, May 1977.

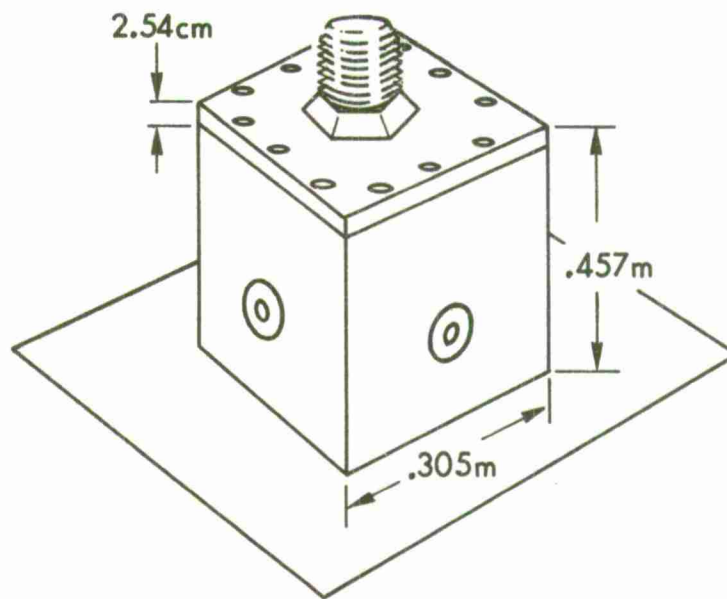


Figure 1. The 1/50th Scale Steel Structure Model.

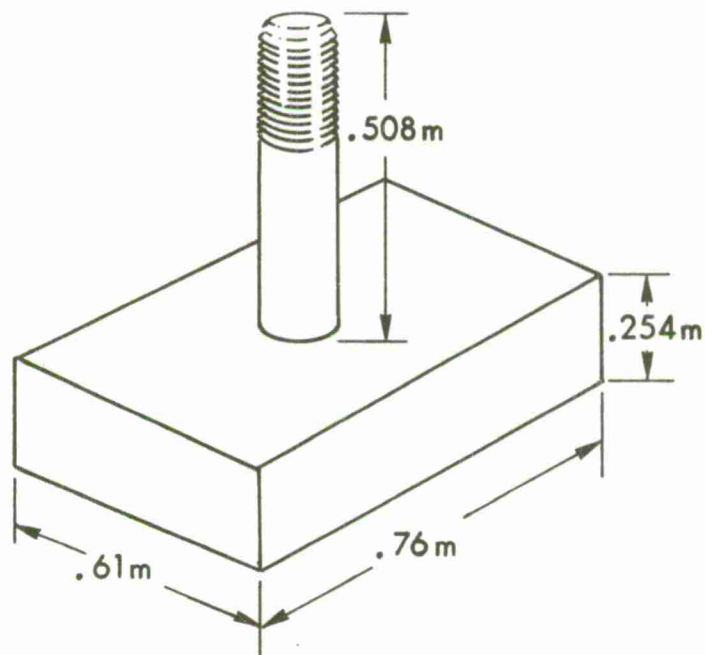


Figure 2. Concrete Mount with Anchor Bolt.

installed and the top plate was bolted in place. An exploded view of the model, mount, and pressure transducers is shown in Figure 3. The model was held in place by tightening the large nut down against the top plate. By loosening the nut, the model orientation could be changed for each test and then retightened. A total of eight models was constructed. The pressure transducers were placed on the center line of a front and side wall at a height of 0.152 m. The model was rotated to change the angle of incidence of the shock front with the model walls.

B. Test Charges

The test charges were cast Pentolite (50 PETN, 50 TNT). The shape was hemispherical and the point of detonation was at the center of the flat side which was placed on the ground surface. The full size charge yield selected for simulation was 125000 kilograms. Therefore, a 1/50 scale model would require (according to cube root scaling) a one-kilogram charge. One-kilogram cast Pentolite charges were used on all of the fifteen tests conducted.

C. Test Instrumentation

The instrumentation for this test series consisted of pressure transducers, magnetic tape recorder/playback, and a data reduction system. A block diagram is shown in Figure 4.

1. Pressure Transducers. Piezoelectric pressure transducers were used for this series of tests. The PCB Electronics Inc., Models 112A22, 113A24, and 113A28, with quartz sensing elements and built-in source followers were used extensively.

2. Tape Recorder System. The tape recorder consisted of three basic units, the power supply and voltage calibrator, the amplifiers, and the FM recorder. The FM tape recorder was a Honeywell 7600 having a frequency response of 80 kHz. Once the signal was recorded on the magnetic tape it was played back and recorded on a Honeywell Visicorder. This oscillograph has 5 kHz frequency response and the overpressure versus time recorded at the individual stations can be read directly from the playback records for preliminary data analysis.

3. Data Reduction System. For the final data output, the tape signals were processed through an analog-to-digital converter, to a digital recorder-reproducer, and then to a computer. The computer (TEKTRONIX 4051) was programmed to apply the calibration values and present the data in the proper units for analysis. From the computer, the data is put on a digital tape from which the final form can be plotted or tabulated. The digital tape can be also stored for future analysis.

D. Test Layout

The test layout was planned to acquire the maximum amount of data for each test conducted. A total of eight peak overpressure levels was selected and therefore eight models were constructed. Twenty-one angles of incidence were selected with eleven bunched between 37.5 and 62.5 degrees in order to document the transition between regular reflection and Mach reflection. The test layout is shown in Figure 5. The peak overpressure

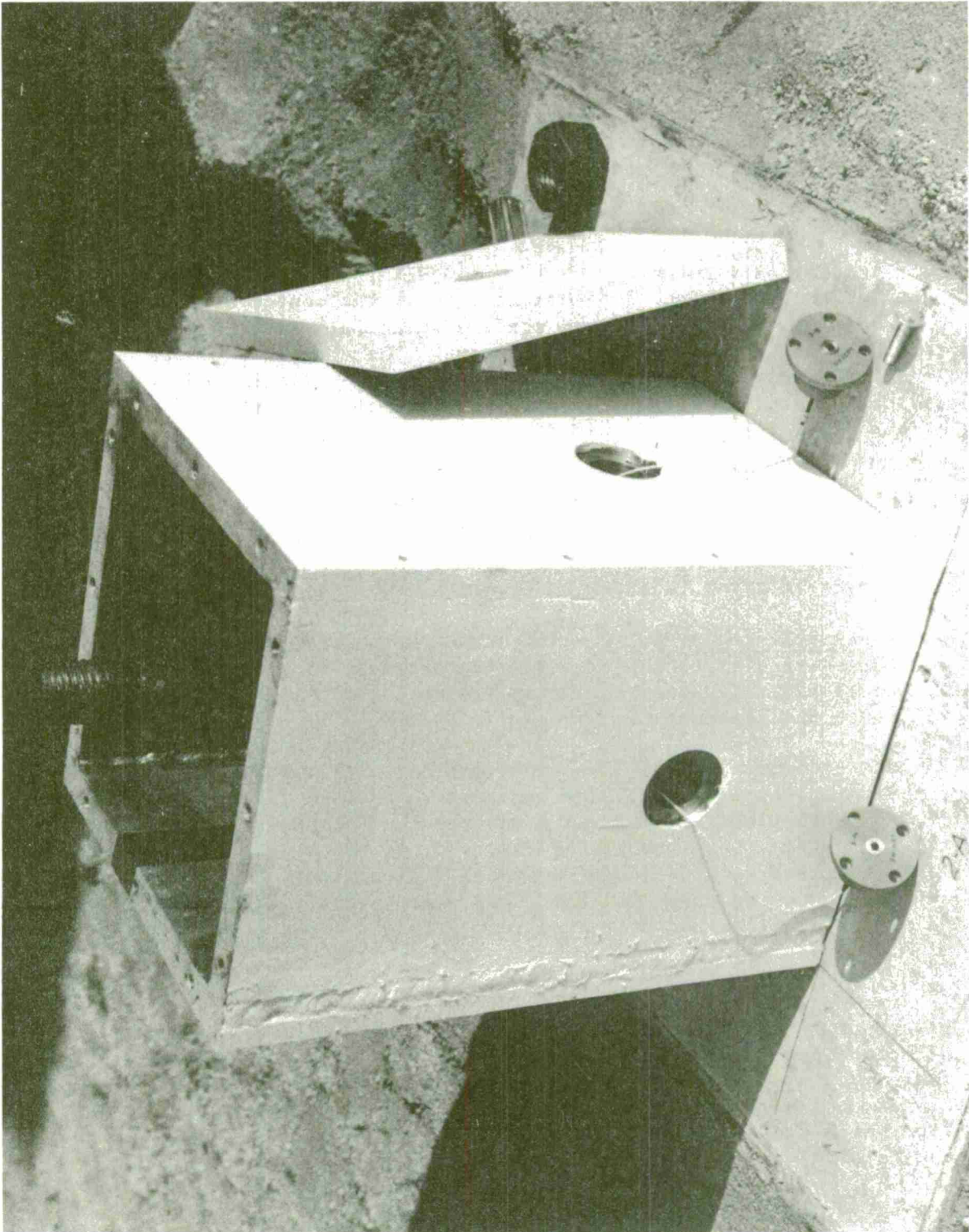


Figure 3. Exploded View of the Model, Mount, and Pressure Transducers.

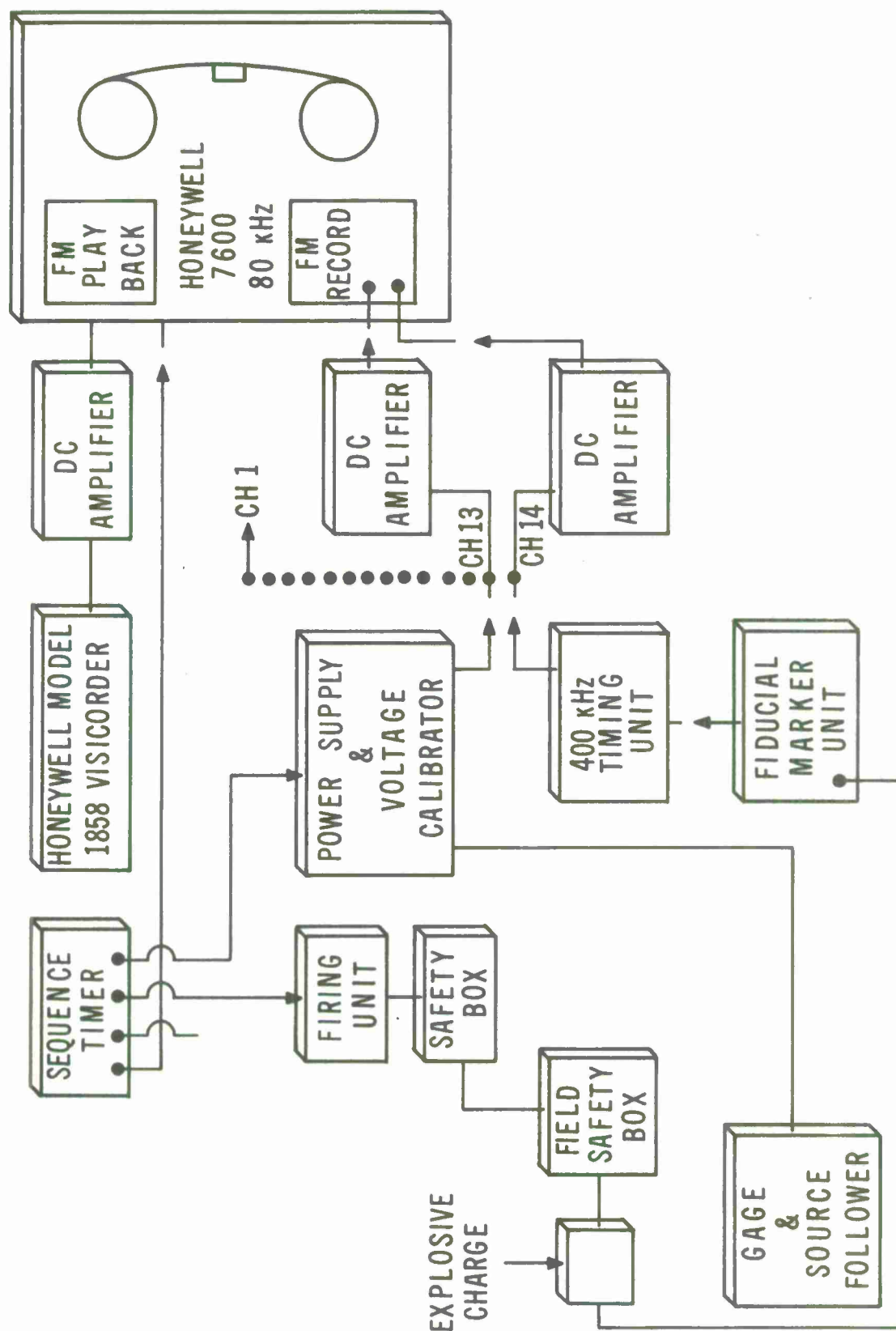


Figure 4. Instrumentation Block Diagram.

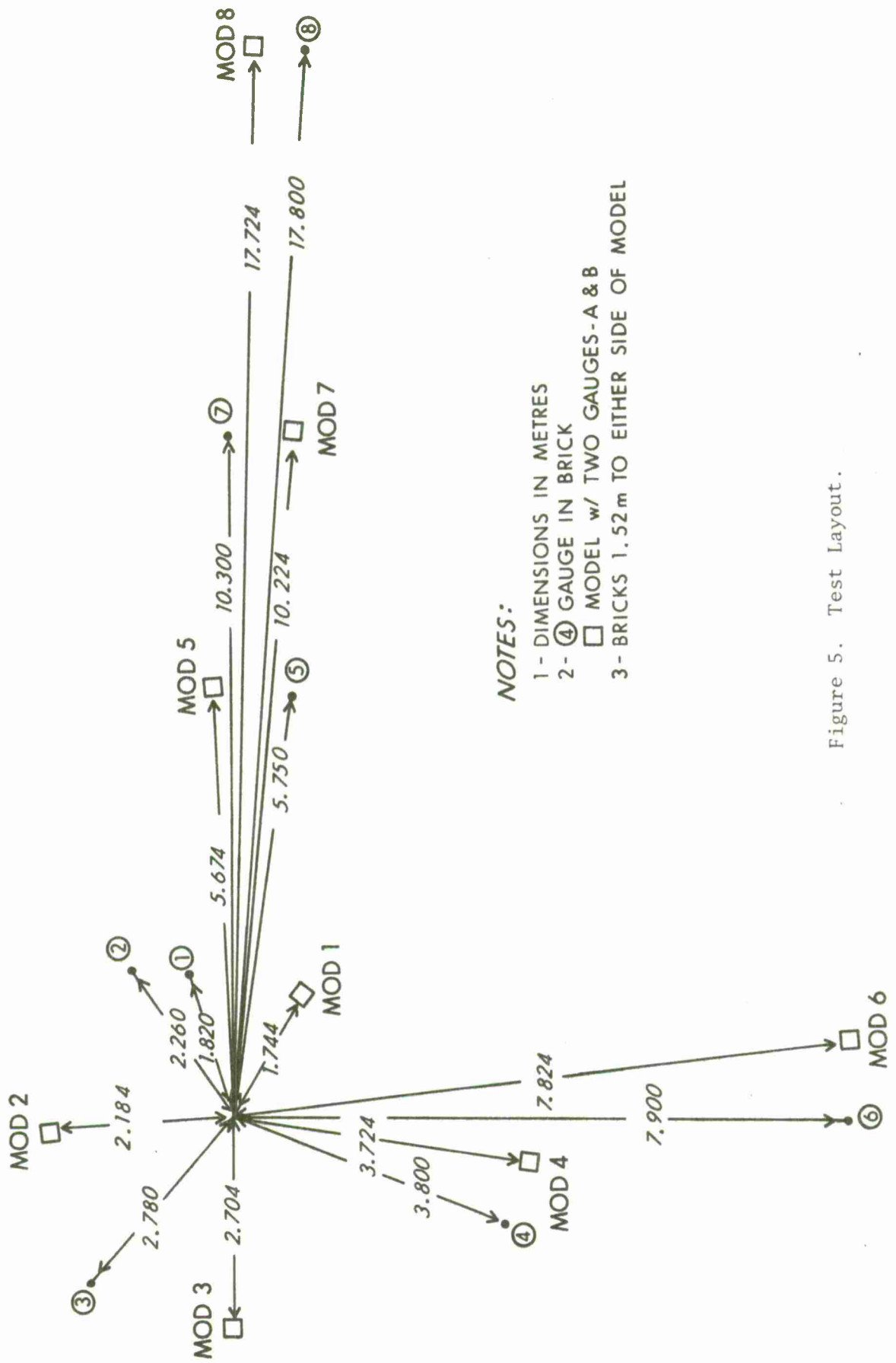


Figure 5. Test Layout.

range of interest for this project was from 345 kPa down to 6.89 kPa. The distances selected to meet the required pressure range were based on the standard TNT hemispherical surface burst curve.⁴ The free-field incident peak overpressure was measured near each structure to provide the input blast parameters. Nomenclature used to identify the gage locations at each station is as follows: Station 1 is the free-field gage, Station 1A is in the front of the model with orientation from 0 to 45 degrees, and Station B is in the side of the model with orientation from 90 to 45 degrees. On Test 1, Station A on all models was at an angle of 0 degrees or normal reflection while Station B on all models was at an angle of 90 degrees or a side-on measurement. The station locations, predicted peak overpressures, and impulses are listed in Table 1 for Test Number 1. The locations of the free-field stations remained the same on all 15 tests. The radial distances for the Stations A and B changed on each shot. A photograph showing Structures 2 (foreground), 1, 4, and 6 for 0 degree and 90 degree orientation with a 1 kg charge in place is presented in Figure 6.

E. Test Matrix

Eight model structures were placed at the distances shown in Table 1 to receive the predicted input pressure and impulse. After each test, each model was rotated the same number of degrees in order that the shock front would strike each set of structure walls at the same angles of incidence. The angle of incidence for Tests 1 - 12 is listed in Table 2. On Tests 13, 14, and 15 the structure models were exposed at different angles and at different pressure levels. These exposures are listed in Table 3.

F. Predictive Approach

There are many references in which the enhancement of peak overpressure as a function of angle of incidence is reported. One of the more complete treatments is given in Reference 5. Normal reflection or head-on reflection can be predicted for the range of incident overpressures of interest in these tests using the following equation:

$$P_r = 2 P_s \left(\frac{7 P_o + 4 P_s}{7 P_o + P_s} \right) \quad (1)$$

where P_o = Ambient atmospheric pressure,
 P_r = Normal reflected overpressure, and
 P_s = Side-on incident overpressure.

This is valid where the ratio of specific heat (γ) for air is a constant 1.4. The equation is good only for predicting the reflected pressure when the models are in the 0-degree orientation, face-on.

⁴ C.N. Kingery, "Air Blast Parameters versus Distance for Hemispherical Surface Bursts," BRL Report 1344, September 1966 (AD 811673).

⁵ "Nuclear Weapons Blast Phenomena, Volume II, Blast Wave Interaction," DASA 1200-II, 1 December 1970 (Confidential RD).

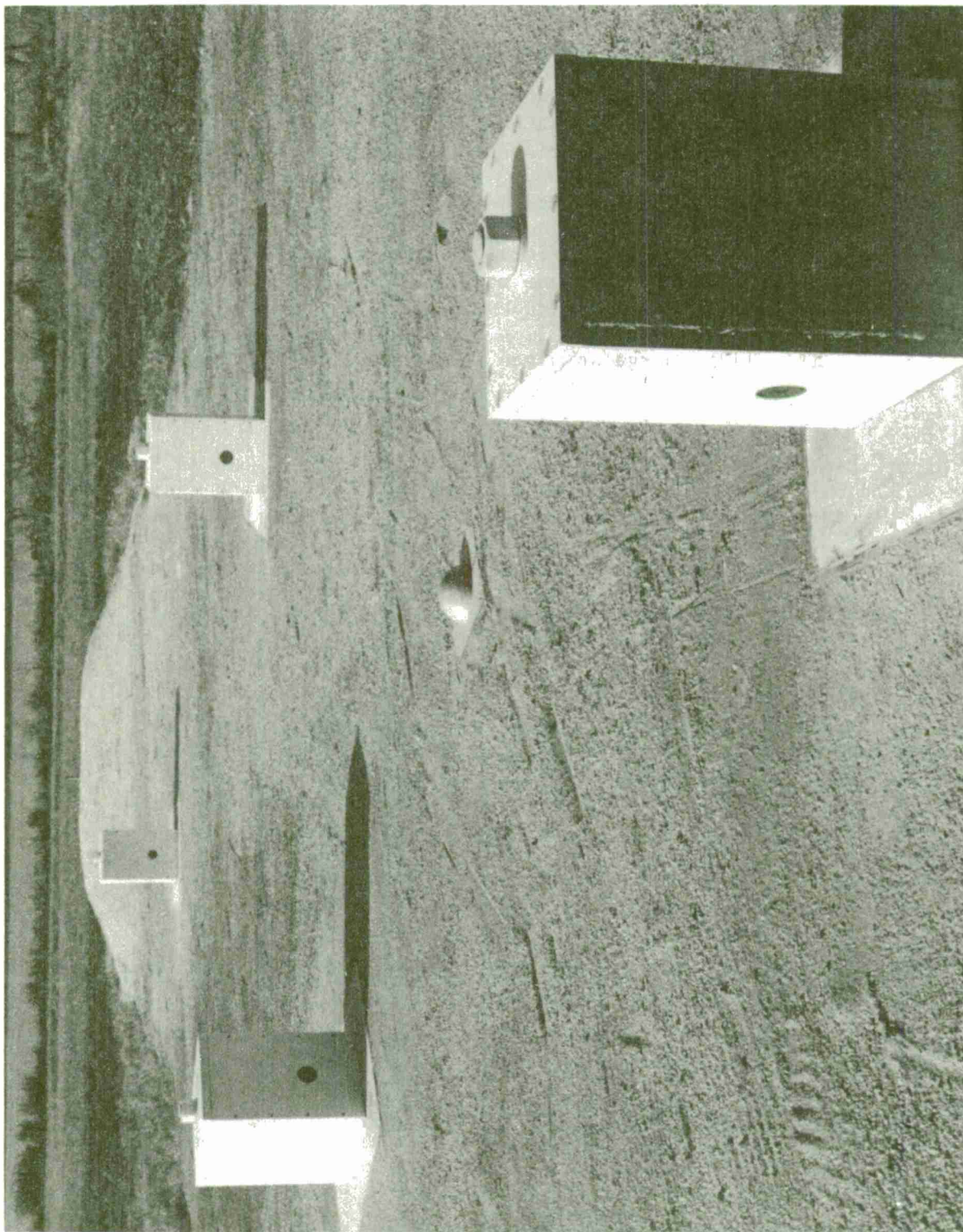


Figure 6. Photograph of Models 2, 1, 4, and 6 with 0 and 90 Degree Orientation.

TABLE 1. PREDICTED PEAK PRESSURES AND IMPULSES FOR TEST 1

Station	Distance m	Pressure kPa	Impulse kPa-ms	Station	Distance m	Pressure kPa	Impulse kPa-ms
1	1.82	345	145	5	5.75	34.5	51
1A	1.74	1361	430	5A	5.67	78.7	110
1B	1.90	340	140	5B	5.83	33.9	50
2	2.26	207	120	6	7.90	20.7	39
2A	2.18	695	320	6A	7.82	44.9	80
2B	2.34	190	112	6B	7.98	20.8	38
3	2.78	138	98	7	10.30	13.8	30
3A	2.70	408	250	7A	10.22	29.1	59
3B	2.86	130	96	7B	10.38	13.7	30
4	3.80	68.9	74	8	17.80	6.89	18
4A	3.72	164	170	8A	17.72	14.7	32
4B	3.88	66.0	72	8B	17.88	6.89	18

TABLE 2. MODEL ORIENTATION, TESTS 1-12

Test No.	Angle of Incidence	Test No.	Angle of Incidence
1	A 0	7	A 37.5
2	B 90	8	B 52.5
3	A 10	9	A 40.5
4	B 80	10	B 49.5
5	A 16	11	A 42.5
6	B 74	12	B 47.5
	A 21		A 43.5
	B 69		B 46.5
	A 27.5		A 45
	B 62.5		B 45
	A 34		A 0
	B 56		B 90

*Tests 1 through 12 all models had same orientation

TABLE 3. MODEL ORIENTATION, TESTS 13-15

Station Test	1	2	3	4	5	6	7	8
	A	B	A	B	A	B	A	B
13	34	56	40.5	49.5	37.5	52.5	37.5	52.5
14	37.5	52.5	40.5	49.5	47.5	40.5	0	40.5
15	43.5	46.5	16	74	21	69	16	74

**On Tests 13, 14, and 15 models were oriented for repeat exposure at selected angles and pressure levels.

A second source used for predicting the reflected pressure in the regular reflection region for different angles of incidence is Reference 6. This report is based on a theoretical treatment by J. Von Newman. It considers the shock wave reflecting on an infinite plane as in a height of burst study. The reference does not treat impulse.

A newer source, Reference 7, treats both the enhancement of pressure in the regular reflection on rising slopes as well as the enhancement in the Mach reflection region on rising slopes. The reflected pressure versus incident pressure undergoing regular reflection for various rising slopes (Figure 12 from Reference 7) is presented as Figure 7. The reflected pressure versus incident pressure undergoing Mach reflection for various rising slopes (Figure 5 from Reference 7) is presented as Figure 8.

A family of curves from Reference 8 showing the reflection factor or pressure ratio P_r/P_s for selected input pressures (P_s) versus angle of incidence are presented in Figure 9. They were used in predicting the reflected pressure, P_r , expected to load the model. These curves and the other predictive methods will be compared with the field measurements.

III. RESULTS

As mentioned in the introduction, the primary objective of this project is to determine the enhancement of overpressure impulse as a function of the angle of incidence of the shock front striking an isolated structure. Presented in Section F of Test Procedures are predictive approaches for determining the peak reflected pressure, but there is a lack of information on predicting the reflected impulse other than normal or head-on. Information that is available is from various height of burst studies, where the reflection process is on an infinite plane.

The results will be presented in the form of reflected pressure compared to side-on pressure or reflected pressure ratios (P_r/P_s). This comparison will also be done for impulse where ratios of I_r/I_s will be developed for angle of incidence and a variety of side-on or free-field impulses.

-
- ⁶ C.N. Kingery and B.F. Pannill, "Parametric Analysis of Regular Reflection of Air Blast," BRL Report 1249, June 1964 (AD 444997).
 - ⁷ Kenneth Kaplan, "Effects of Terrain on Blast Prediction Methods and Prediction," BRL Contract Report ARBRL-CR-00355, January 1978 (AD A051350).
 - ⁸ H. L. Brode, "Height of Burst Effects at High Overpressures," The Rand Corporation, RM-6301, DASA 2506, July 1970.

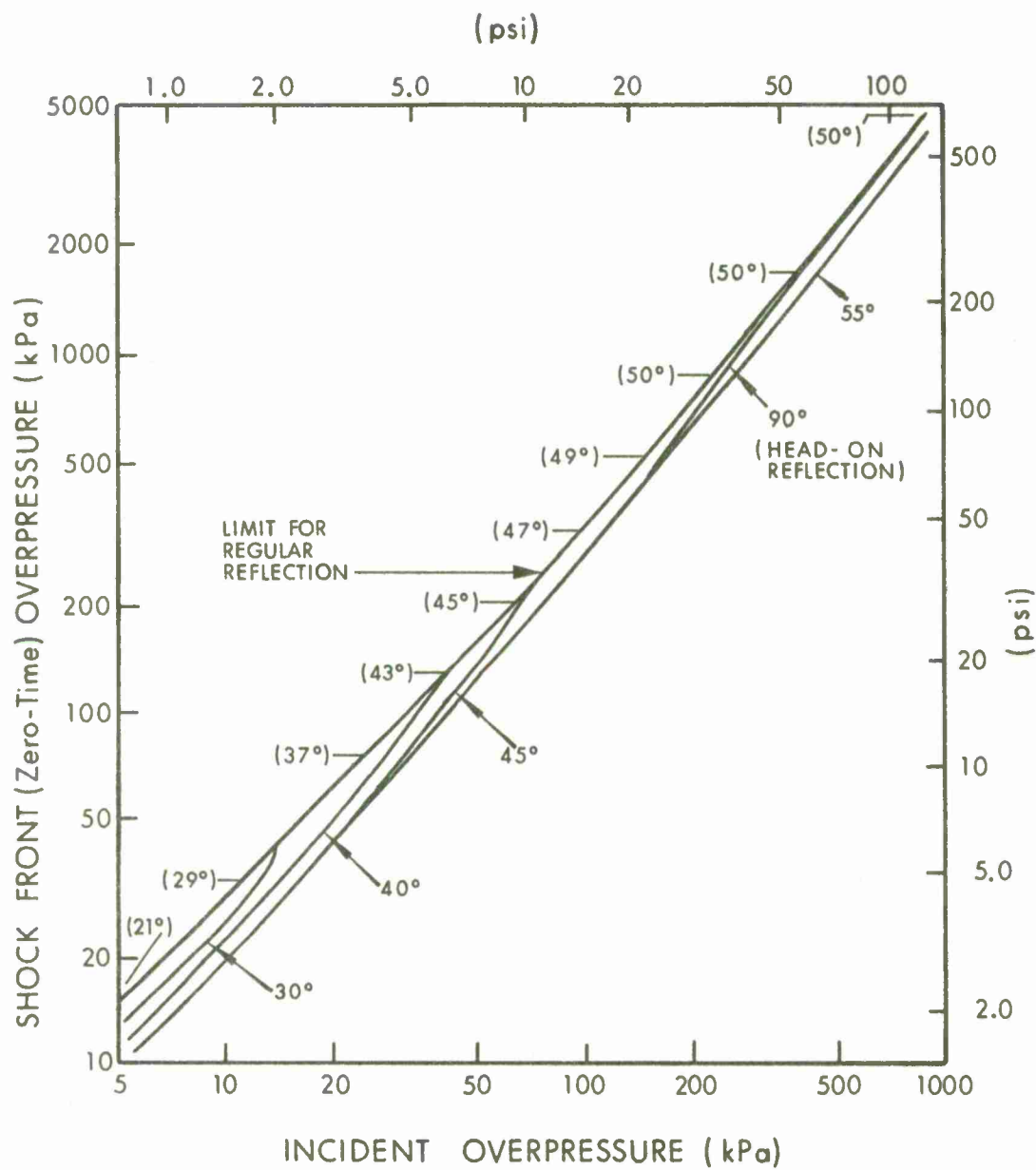


Figure 7. Reflected Pressure versus Incident Overpressure for a Shock Wave Undergoing Regular Reflection on a Rising Slope.

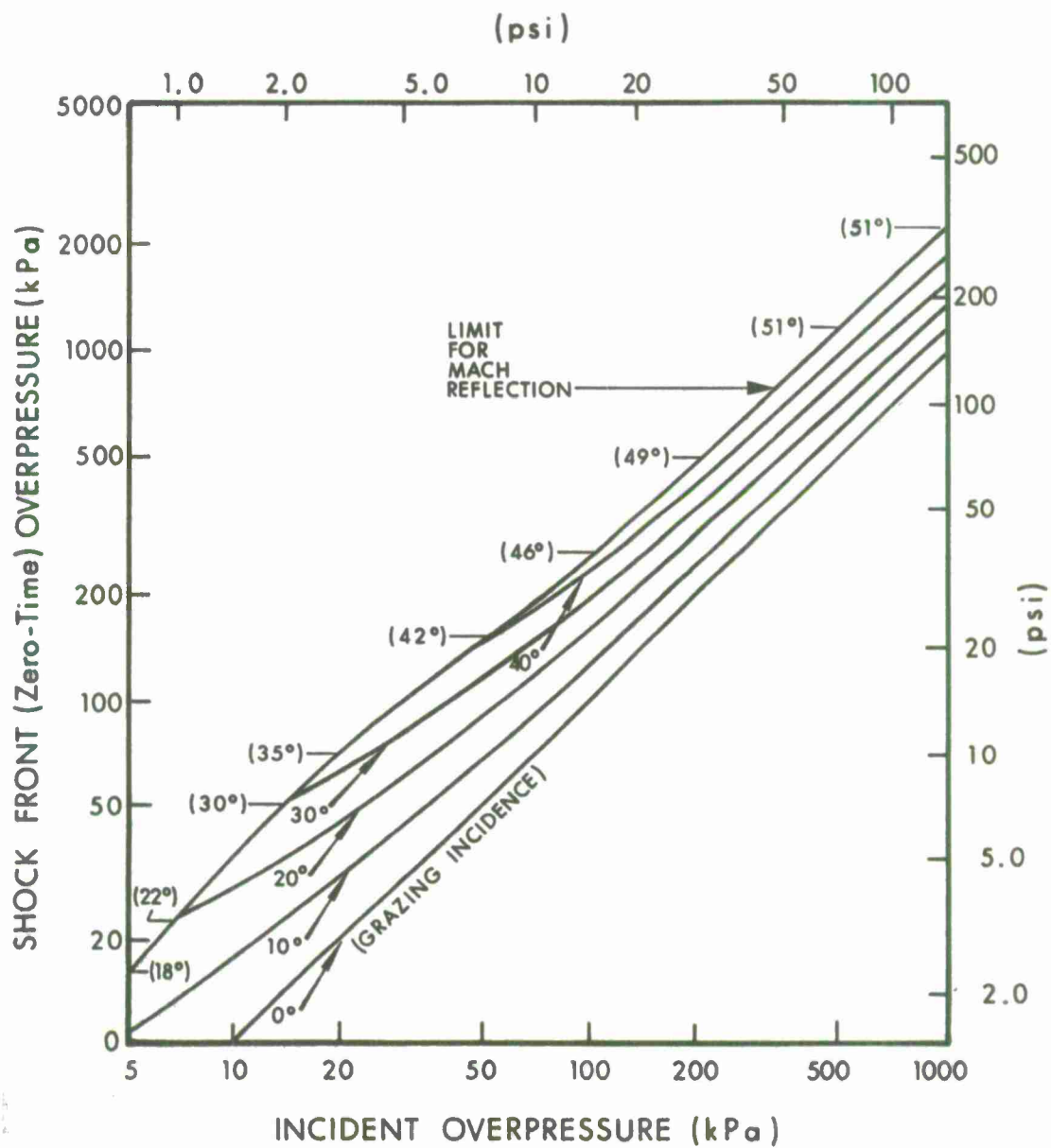


Figure 8. Reflected Pressure versus Incident Overpressure for Shock Waves Undergoing Mach Reflection on a Rising Slope.

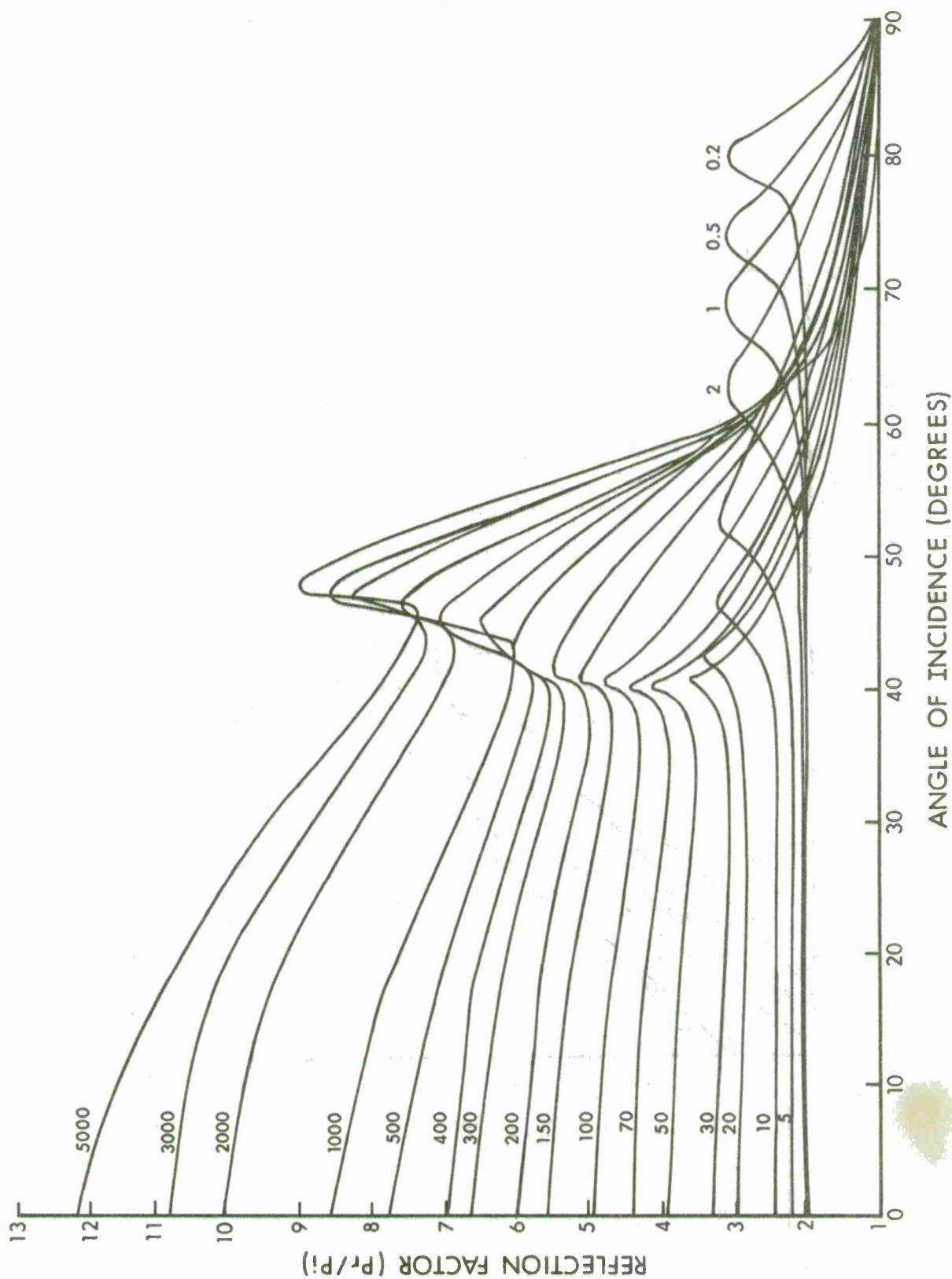


Figure 9. Reflection Factors versus Angle of Incidence for Selected Incident Overpressures.

A. Side-on Overpressure and Impulse Measurements

In order to determine the pressure reflection and impulse reflection ratios, the side-on or incident overpressures and impulses must be established. Eight pressure transducers were placed at the distances and locations shown in Figure 5 to record the incident overpressure versus time of the blast wave. Records were obtained on each test and the incident peak overpressure and incident overpressure impulses are listed in Table 4 for each station. An average value from the fifteen tests was used to plot a peak overpressure versus distance for a 1 kg hemispherical Pentolite surface burst. Over ninety percent of the values of both pressure and impulse fell within a ± 5 percent of the average value established at each station. The average peak incident overpressure (P_g) versus horizontal distances are plotted in Figure 10. The solid lines in Figures 10 and 11 were established from data presented in Reference 9. The average incident impulses (I_g) versus horizontal distances from Table 4 are plotted in Figure 11.

B. Reflected Peak Overpressure and Impulse versus Angle of Incidence

The reflected peak overpressure versus angle of incidence is a direct measurement made on the front and side wall of the model. The reflected impulse is obtained from the integration of the overpressure versus time recorded from Stations A and B located on the model.

The reflected pressure recorded on Stations 1A and 1B through 8A and 8B are plotted versus angle of incidence in Figure 12. The lines through the data points are visual fits and were used to establish the values of reflected pressure listed in Table 5.

The reflected impulses versus angle of incidence recorded at Stations 1A and 1B through 8A and 8B are plotted in Figure 13. The solid lines are visual fits of the data points and were used to determine the values of reflected impulse listed in Table 5.

C. Reflected Pressure and Impulse Ratios versus Angle of Incidence

Both the reflected pressure (P_r) and the reflected impulse (I_r) will be presented as a function of side-on pressure (P_g) and side-on impulse (I_g) in the form of ratios. That is, P_r/P_g and I_r/I_g will be presented versus angle of incidence.

The reflected pressure ratios P_r/P_g were calculated for each angle of incidence at each station and are listed in Table 5. It was noted in the Test Layout Section that Station A and Station B are located at different radial distances (ΔR) but this ΔR becomes less as the model is rotated and $\Delta R = 0$ at 45 degrees angle of incidence. In Table 5 the side-on

(Text continued on page 38)

⁹ Charles Kingery and George Coulter, "TNT Equivalency of Pentolite Hemispheres," ARBRL-TR-02456, December 1982 (AD A123340).

TABLE 4. INCIDENT OVERPRESSURE AND IMPULSE AT FREE-FIELD STATIONS

Test No.	Station 1			Station 2			Station 3			Station 4		
	Distance 1.82			Distance 2.26			Distance 2.78			Distance 3.80		
	P _s kPa	I _s kPa-ms		P _s kPa	I _s kPa-ms		P _s kPa	I _s kPa-ms		P _s kPa	I _s kPa-ms	
1	327	110		169*	103		121*	85		66	68	
2	335	116		227	105		134	88		70	70	
3	332	117		220	100		135	87		69	69	
4	303	113		209	103		127	88		66	66	
5	308	116		196	103		129	86		74	70	
6	307	113		195	102		127	84		71	67	
7	340	117		206	104		129	84		68	68	
8	302	112		201	102		135	84		69	67	
9	N-1	N-1		208*	99		131	86		66	69	
10	N-1	N-1		172	106*		138	83		68*	66*	
11	321*	115		208*	100		135	87		86*	286*	
12	380*	116		190*	105		139	89		68	63	
13	315	121		215	99		139	85		71	67	
14	324	114		206	108		131	91		72	69	
15	292	120		212	104		140	91		69	71	
AVG	317	115.4		208.6	102.6		133.5	86.5		69.1	68.2	

* Questionable value
N-1 - Not instrumented

TABLE 4. INCIDENT OVERPRESSURE AND IMPULSE AT FREE-FIELD STATIONS (CONT)

Test No.	Station 5			Station 6			Station 7			Station 8		
	Distance 5.75			Distance 7.90			Distance 10.3			Distance 17.8		
	P s kPa	I s kPa-ms		P s kPa	I s kPa -ms		P s kPa	I s kPa-ms		P s kPa	I s kPa-ms	
1	39	45		25	34		13.9	24.4		6.1	15.0	
2	40	43		26	35		14.5	25.3		5.9	15.1	
3	42	45		26	36		14.1	25.3		6.2	15.1	
4	41	49		25	35		13.1	25.3		7.4	15.4	
5	41	46		25	35		13.7	25.6		5.8	14.8	
6	39	45		25	35		13.6	25.1		5.7	14.9	
7	39	47		25	35		13.9	25.6		6.7	15.2	
8	39	47		25	35		13.5	25.9		5.2	15.5	
9	40	47		24	34		14.4	24.4		N-1	N-1	
10	38	46		25	35		13.6	24.8		N-1	N-1	
11	40	47		24	36		14.2	25.5		5.9	15.2	
12	41	49		25	35		14.6	26.1		6.1	15.8	
13	39	47		25	36		14.0	26.0		5.9	15.5	
14	41	47		24	36		14.7	26.7		6.9	16.2	
15	41	47		24	36		14.9	25.9		6.7	16.1	
AVG	40.0	46.5		24.9	35.2		14.1	25.4		6.27	15.4	

N-1 - Not instrumented

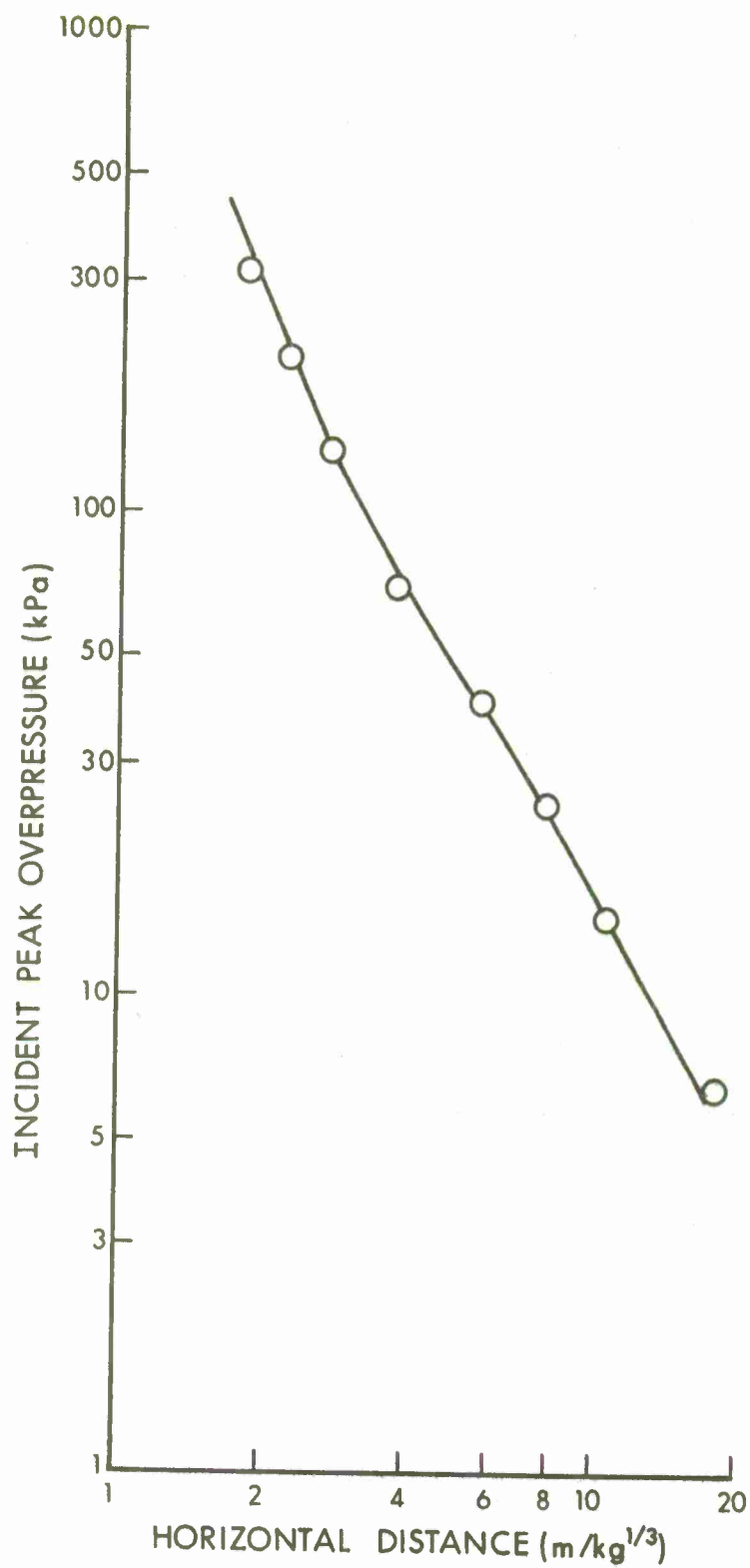


Figure 10. Peak Incident Overpressure versus Scaled Distance for a 1 kg Hemispherical Surface Burst.

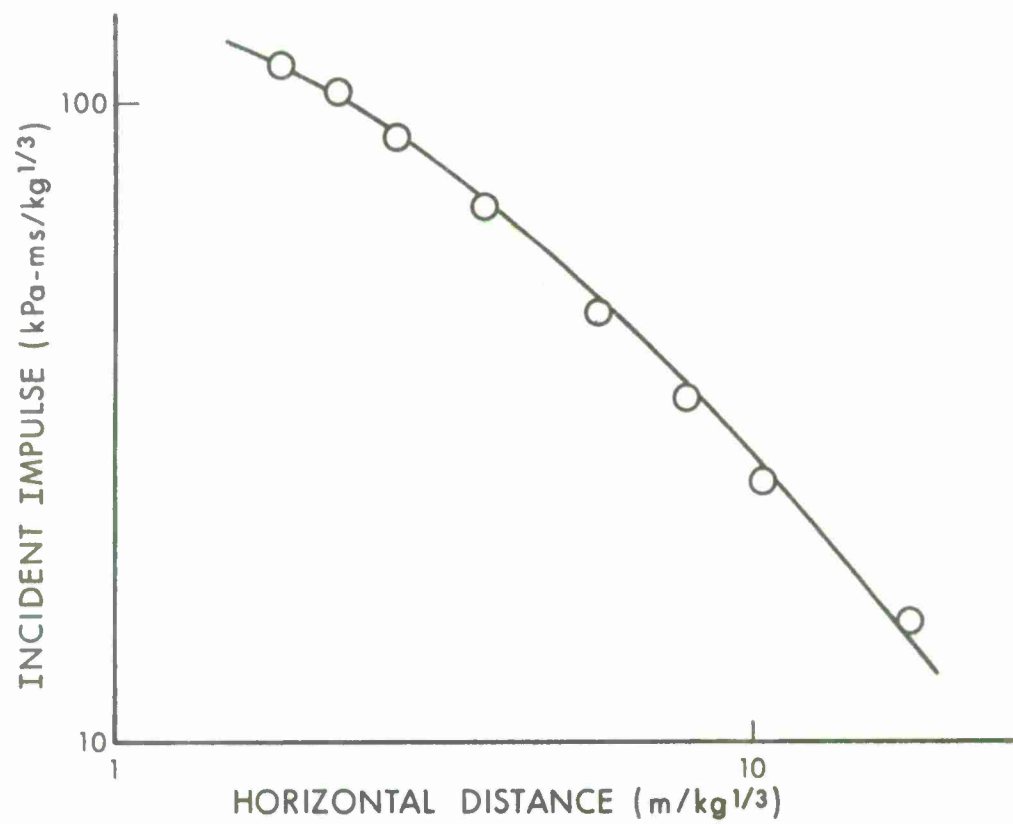


Figure 11. Incident Scaled Impulse versus Scaled Distance for a 1 kg Hemispherical Surface Burst.

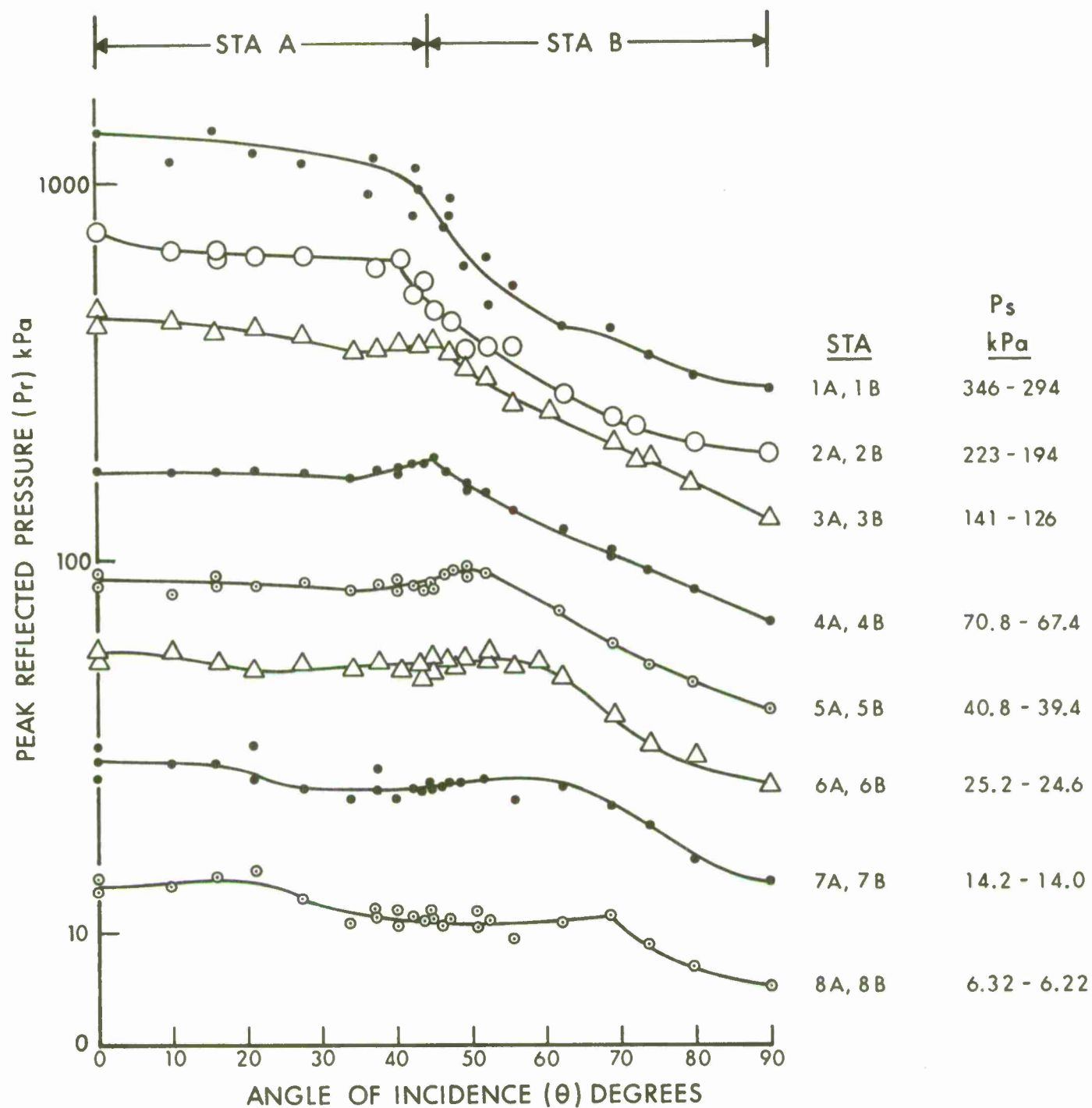


Figure 12. Peak Reflected Pressure versus Angle of Incidence for Stations 1 through 8.

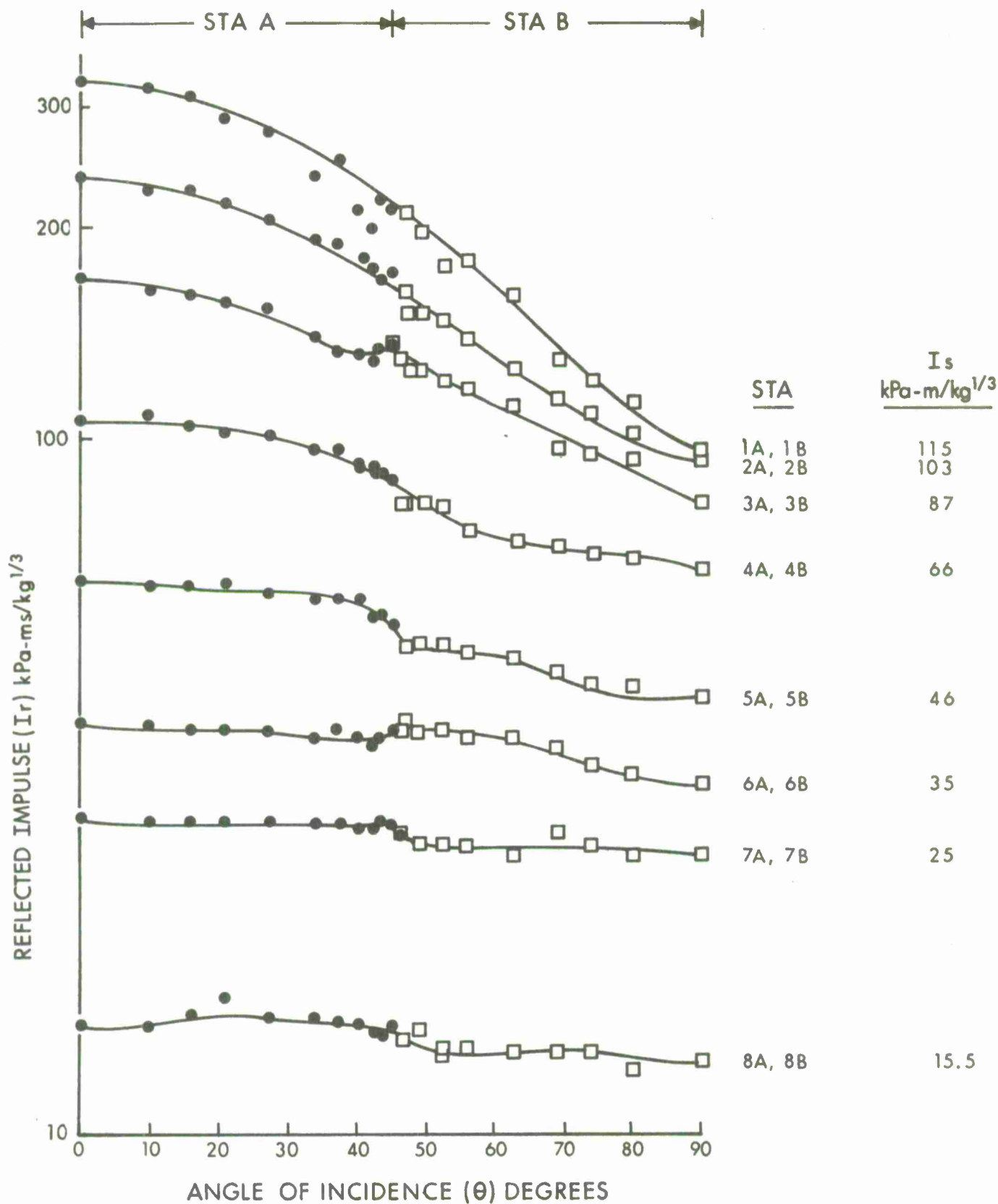


Figure 13. Scaled Reflected Impulse versus Angle of Incidence for Stations 1 through 8.

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE

Station 1A, $P_s^* = 346$, $I_s^* = 118$				Station 1B, $P_s = 294$, $I_s = 113$			
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg $1/3$	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg $1/3$
0	1367	3.95	331	90	294	1.00	97
10	1310	3.81	325	80	310	1.06	114
16	1300	3.79	315	74	350	1.14	122
21	1280	3.74	291	69	390	1.25	130
27.5	1240	3.66	279	62.5	440	1.39	162
34	1200	3.57	237	56	500	1.56	180
37.5	1130	3.39	256	52.5	570	1.76	177
40.5	1050	3.16	213	49.5	650	1.99	200
42.5	950	2.88	201	47.5	750	2.29	211
43.5	900	2.73	221	46.5	812	2.48	212
45	850	2.58	215	45	850	2.58	215

**NSWC formula*

**NSWC formula:*

* P_s unit - kPa

I_s unit = kPa-ms

$$i_\theta = i_{90} (1 + \cos\theta - 2 \cos^2\theta) + i_0 \cos^2\theta$$

$$\frac{i_\theta}{i_{90}} = \left[\left(\frac{i_0}{i_{90}} - 2 \right) \cos\theta + 1 \right] \cos\theta + 1$$

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 2A, $P_s = 223$, $I_s = 105$										Station 2B, $P_s = 194$, $I_s = 100$									
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s
0	760	3.41	240	2.29	90	194	1.00	94	0.94										
10	690	3.09	232	2.21	80	205	1.03	104	1.03										
16	650	2.93	230	2.19	74	224	1.11	110	1.09										
21	650	2.94	220	2.10	69	240	1.18	116	1.14										
27.5	650	2.95	210	2.02	62.5	277	1.34	129	1.26										
34	640	2.94	195	1.88	56	325	1.55	140	1.36										
37.5	620	2.86	192	1.85	52.5	370	1.75	149	1.45										
40.5	510	2.59	183	1.76	49.5	410	1.93	152	1.48										
42.5	520	2.42	175	1.68	47.5	430	2.02	151	1.47										
43.5	520	2.33	170	1.65	46.5	460	2.16	164	1.59										
45	480	2.25	173	1.68	45	480	2.25	173	1.68										

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 3A, $P_s = 141$, $I_s = 88$										Station 3B, $P_s = 126$, $I_s = 84$									
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s
0	433	3.07	172	1.95	90	126	1.00	81	0.96	90	126	1.00	81	0.96	90	126	1.00	81	0.96
10	431	3.06	165	1.88	80	160	1.25	94	1.13	80	160	1.25	94	1.13	80	160	1.25	94	1.13
16	420	2.98	163	1.85	74	184	1.40	96	1.23	74	184	1.40	96	1.23	74	184	1.40	96	1.23
21	405	2.89	159	1.81	69	206	1.57	97	1.31	69	206	1.57	97	1.31	69	206	1.57	97	1.31
27.5	390	2.81	155	1.76	62.5	235	1.77	112	1.41	62.5	235	1.77	112	1.41	62.5	235	1.77	112	1.41
34	360	2.61	140	1.59	56	275	2.05	118	1.51	56	275	2.05	118	1.51	56	275	2.05	118	1.51
37.5	365	2.64	134	1.52	52.5	305	2.26	123	1.56	52.5	305	2.26	123	1.56	52.5	305	2.26	123	1.56
40.5	380	2.77	134	1.54	49.5	330	2.43	127	1.60	49.5	330	2.43	127	1.60	49.5	330	2.43	127	1.60
42.5	380	2.77	131	1.51	47.5	348	2.56	127	1.65	47.5	348	2.56	127	1.65	47.5	348	2.56	127	1.65
43.5	385	2.81	136	1.56	46.5	362	2.66	131	1.63	46.5	362	2.66	131	1.63	46.5	362	2.66	131	1.63
45	390	2.87	138	1.59	45	390	2.87	138	1.59	45	390	2.87	138	1.59	45	390	2.87	138	1.59

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 4A, $P_s = 70.8$, $I_s = 69$										Station 4B, $P_s = 67.4$, $I_s = 67$									
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s
0	177	2.50	107	1.55	90	69	1.02	64	0.96										
10	175	2.48	109	1.58	80	84	1.25	67	1.00										
16	178	2.52	106	1.54	74	92	1.35	68	1.00										
21	178	2.52	103	1.49	69	103	1.50	70	1.03										
27.5	172	2.44	101	1.46	62.5	122	1.77	72	1.06										
34	161	2.38	96	1.39	56	138	1.99	74	1.07										
37.5	176	2.52	97	1.41	52.5	157	2.26	82	1.21										
40.5	178	2.55	92	1.33	49.5	164	2.36	82	1.19										
42.5	183	2.61	91	1.32	47.5	172	2.47	80	1.16										
43.5	183	2.61	90	1.30	46.5	173	2.48	81	1.17										
45	189	2.71	89	1.29	45	189	2.71	89	1.29										

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 5A, $P_s = 40.8$, $I_s = 47$										Station 5B, $P_s = 39.4$, $I_s = 46$									
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s
0	93	2.28	63	1.34	90	40	1.02	42	0.91	0.91									
10	89	2.18	62	1.32	80	48	1.21	44	0.96	1.05									
16	88	2.16	62	1.32	74	52	1.31	44	0.96	1.12									
21	87	2.14	62	1.32	69	60	1.50	41	1.00	1.17									
27.5	88	2.16	60	1.28	62.5	73	1.83	48	1.04	1.23									
34	84	2.07	59	1.25	56	83	2.06	49	1.04	1.27									
37.5	85	2.10	59	1.25	52.5	91	2.26	50	1.06	1.29									
40.5	87	2.15	59	1.25	49.5	94	2.34	50	1.06	1.30									
42.5	86	2.13	55	1.17	47.5	93	2.31	49	1.04	1.30									
43.5	85	2.10	56	1.19	46.5	91	2.25	50	1.06	1.31									
45	88	2.18	54	1.15	45	88	2.18	54	1.15										

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 6A, $P_s = 25.2$, $I_s = 35$										Station 6B, $P_s = 24.6$, $I_s = 35$									
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s
0	56	2.22	39	1.11	90	25	1.02	32	0.91										
10	56	2.22	39	1.11	80	29	1.17	33	0.94										
16	52	2.06	38	1.09	74	32	1.30	34	0.97										
21	50	1.98	38	1.09	69	38	1.53	36	1.03										
27.5	52	2.07	38	1.09	62.5	48	1.93	37	1.06										
34	51	2.03	37	1.06	56	52	2.09	37	1.06										
37.5	52	2.07	38	1.09	52.5	54	2.17	38	1.09										
40.5	50	2.00	37	1.06	49.5	53	2.12	38	1.09										
42.5	501	2.00	36	1.03	47.5	51	2.04	39	1.11										
43.5	50	2.009	36	1.03	46.5	52	2.08	38	1.09										
45	52	2.08	38	1.09	45	52	2.08	38	1.09										

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 7A, $P_s = 14.2$, $I_s = 25$										Station 7B, $P_s = 14.0$, $I_s = 25$									
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s
0	30	2.11	28.7	1.15	90	14	1.00	25.0	1.00										
10	29	2.04	28.0	1.12	80	16	1.14	25.0	1.00										
16	29	2.04	28.0	1.12	74	20	1.43	26.0	1.04										
21	29	2.04	28.0	1.12	69	22	1.57	27.0	1.08										
27.5	26	1.83	28.0	1.12	62.5	25	1.79	25.0	1.00										
34	25	1.77	28.0	1.12	56	26	1.84	26.0	1.04										
37.5	26	1.84	28.0	1.12	52.5	26	1.84	26.0	1.04										
40.5	25	1.77	27.5	1.10	49.5	26	1.84	26.0	1.04										
42.5	25	1.77	27.5	1.10	47.5	26	1.84	26.0	1.04										
43.5	25	1.77	28.0	1.12	46.5	25	1.80	27.0	1.08										
45	25	1.80	28.0	1.12	45	25	1.80	28.0	1.12										

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 8A, $P_s = 6.32$, $I_s = 15.5$										Station 8B, $P_s = 6.22$, $I_s = 15.4$									
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg ^{1/3}	IMP REFL FACTOR I_r/I_s
0	13.2	2.09	14.2	0.92	90	7.2	1.16	12.6	0.82										
10	13.5	2.14	14.2	0.92	93	8.2	1.31	12.2	0.79	0.94									
16	14.0	2.21	14.8	0.95	94	9.9	1.58	13.2	0.86	0.99									
21	14.0	2.21	15.6	1.01	96	11.0	1.76	13.1	0.85	1.02									
27.5	12.4	1.97	14.6	0.94	98	10.9	1.74	13.1	0.85	1.04									
34	11.2	1.77	14.5	0.94	101	10.5	1.67	13.1	0.85	1.05									
37.5	11.3	1.79	14.5	0.94	102	10.9	1.74	13.0	0.84	1.05									
40.5	11.3	1.79	14.4	0.93	103	11.0	1.75	14.0	0.91	1.05									
42.5	11.1	1.76	13.9	0.90	103	11.0	1.75	13.5	0.88	1.04									
43.5	10.8	1.72	13.8	0.89	104	11.0	1.75	13.5	0.88	1.04									
45	11.4	1.81	14.3	0.93	104	11.4	1.81	14.3	0.93										

pressure (P_g) for a θ of 0 degrees is listed for Station A and the P_g for 90 degrees is listed for Station B. The P_g for each radial distance from $\theta = 0$ degree through $\theta = 90$ degrees was calculated to insure that the correct P_g for each angle was used in determining the ratio P_r/P_g . The values listed in Table 5 are plotted in Figures 14 and 15.

The reflected impulse ratios listed in Table 5 are based on the reflected impulse curves plotted in Figure 13 and the side-on impulse listed in Table 4 adjusted for the R distance between Station A and B. The range of side-on impulses is listed for each station in Table 5. The values of reflected impulse I_r divided by the side-on impulse I_g listed in Table 5 are plotted in Figure 16.

IV. DISCUSSION

The data tables and plotted curves presented in the Results section show trends of the effects on reflected pressure and impulse, of the angle of incidence of the shock front striking an isolated structure. Some of these trends follow theory and predictions as presented in the Predictive Approach of the Test Procedures section while other results are different.

A. Reflected Pressure in the Regular and Mach Reflection Regions

The curve showing reflective pressure (P_r) as a function of incident pressure (P_g) for all angles of incidence in the regular reflection region is shown in Figure 17. This curve is quite similar to the family of curves presented in Figure 7. Note in Figure 7 the slope angles are identified rather than the angle of incidence. The spread of data is indicated by the band at each station location. This means that when a particular station receives the same incident pressure (P_g) and as the model is rotated to change the angle of incidence the reflected pressure (P_r) does not change greatly in the regular reflection region. This is shown graphically in Figure 12.

The family of curves presented in Figure 18 show a trend similar to that presented in Figure 8 for pressure enhancement in the Mach reflection region. The quantitative values are higher in Figure 8 than measured experimentally in Figure 18. This difference is because the measured values from this series did not record the enhancement at the transition zone from the regular reflection region to the Mach reflection region as shown in Figure 9. The enhancement shown in Figure 9 is of very short duration and would have little effect on impulse in the blast wave.

B. Reflected Impulse in the Regular and Mach Reflection Regions

The reflected impulse versus incident impulse and angle of incidence is presented in Figure 13. A variation of this presentation is made in Figure 19 where the data is plotted for reflected impulse I_r as a function of incident impulse (I_g) in the regular reflection region. The two solid lines show the variation in reflected impulse measured on an isolated structure when the angle of incidence is in the regular reflection region.

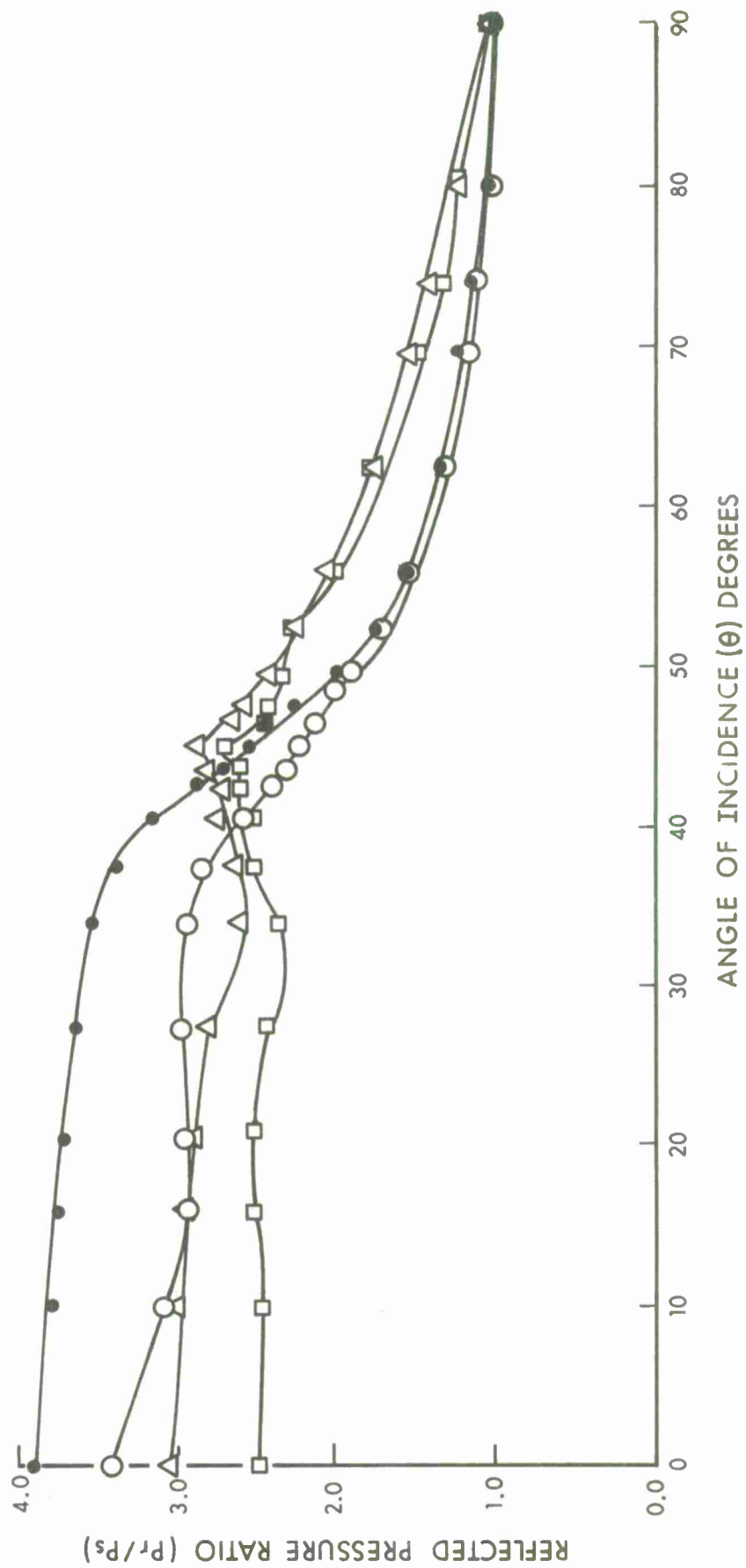


Figure 14. Reflected Pressure Ratios (P_r/P_s) versus Angle of Incidence for P_s from 346 kPa to 67.4 kPa.

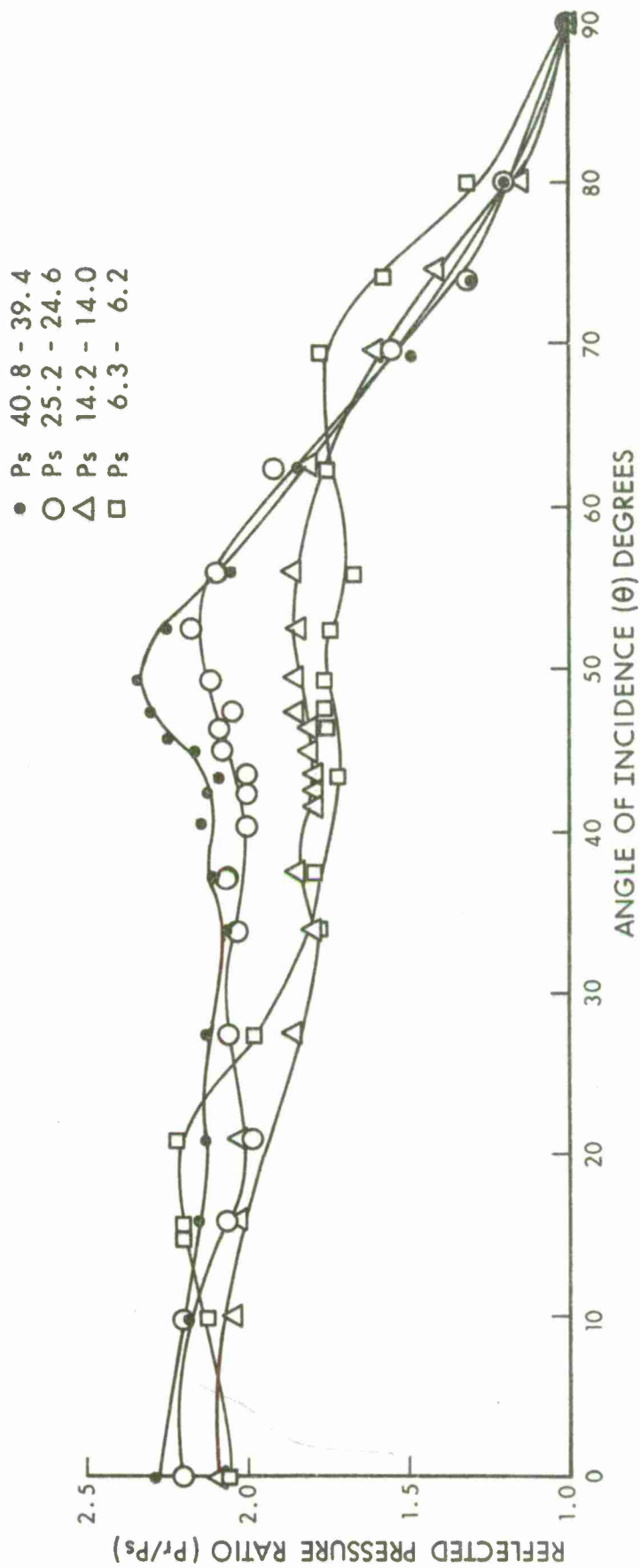


Figure 15. Reflected Pressure Ratios (P_r/P_s) versus Angle of Incidence for P_s from 40.8 kPa to 6.2 kPa.

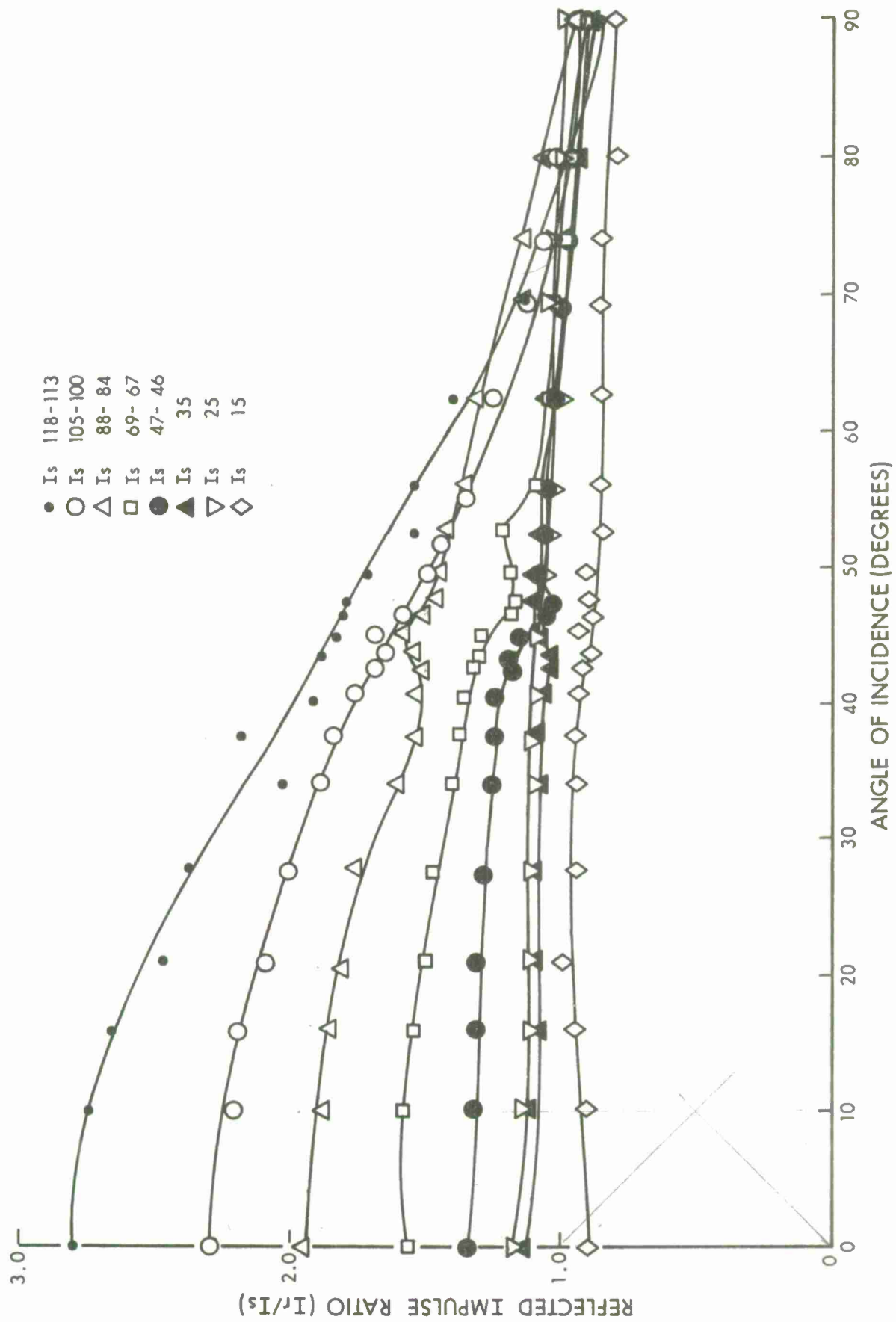


Figure 16. Reflected Impulse Ratios (I_r/I_s) versus Angle of Incidence.

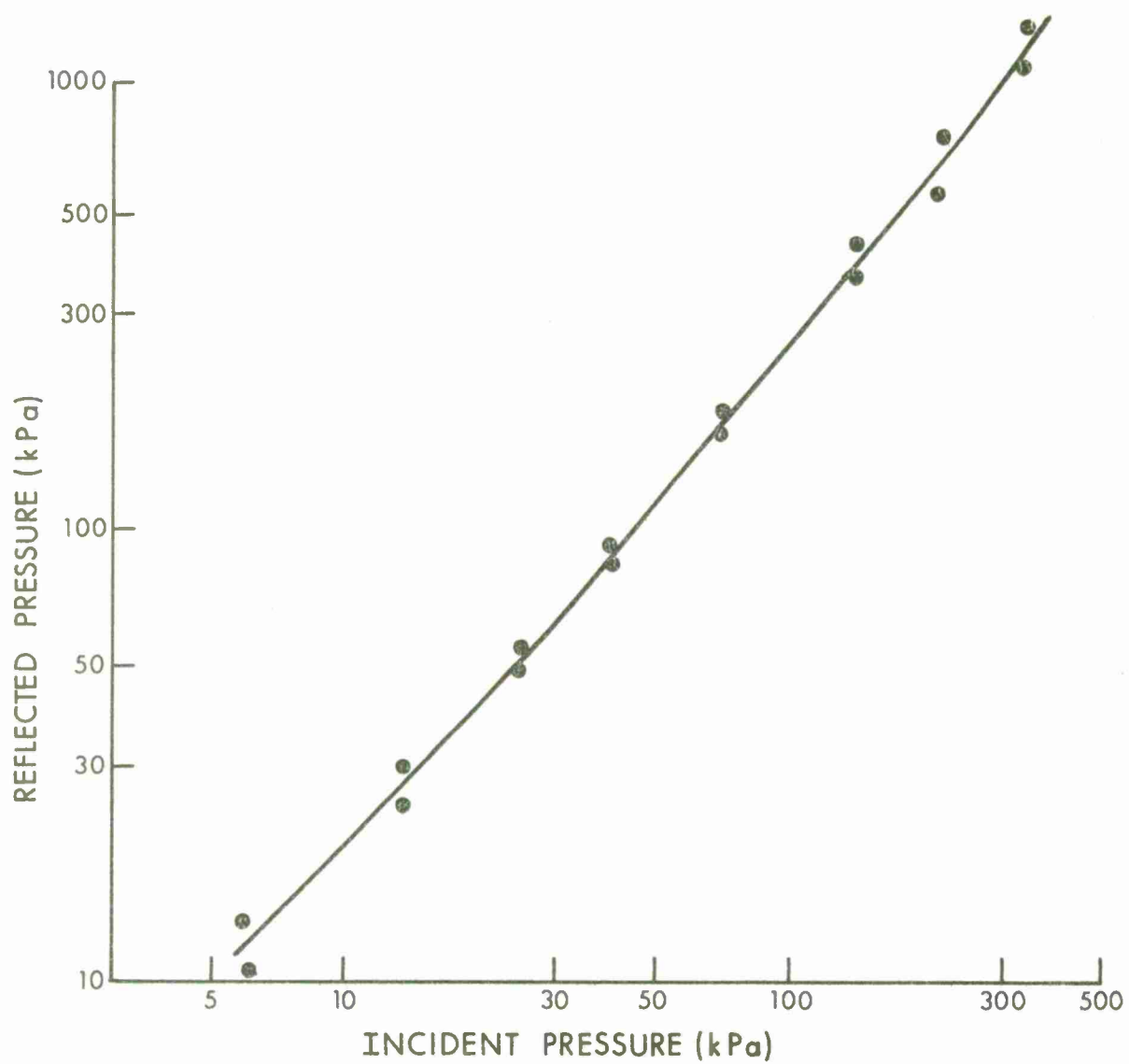


Figure 17. Reflected Pressure versus Incident Pressure in the Regular Reflection Region.

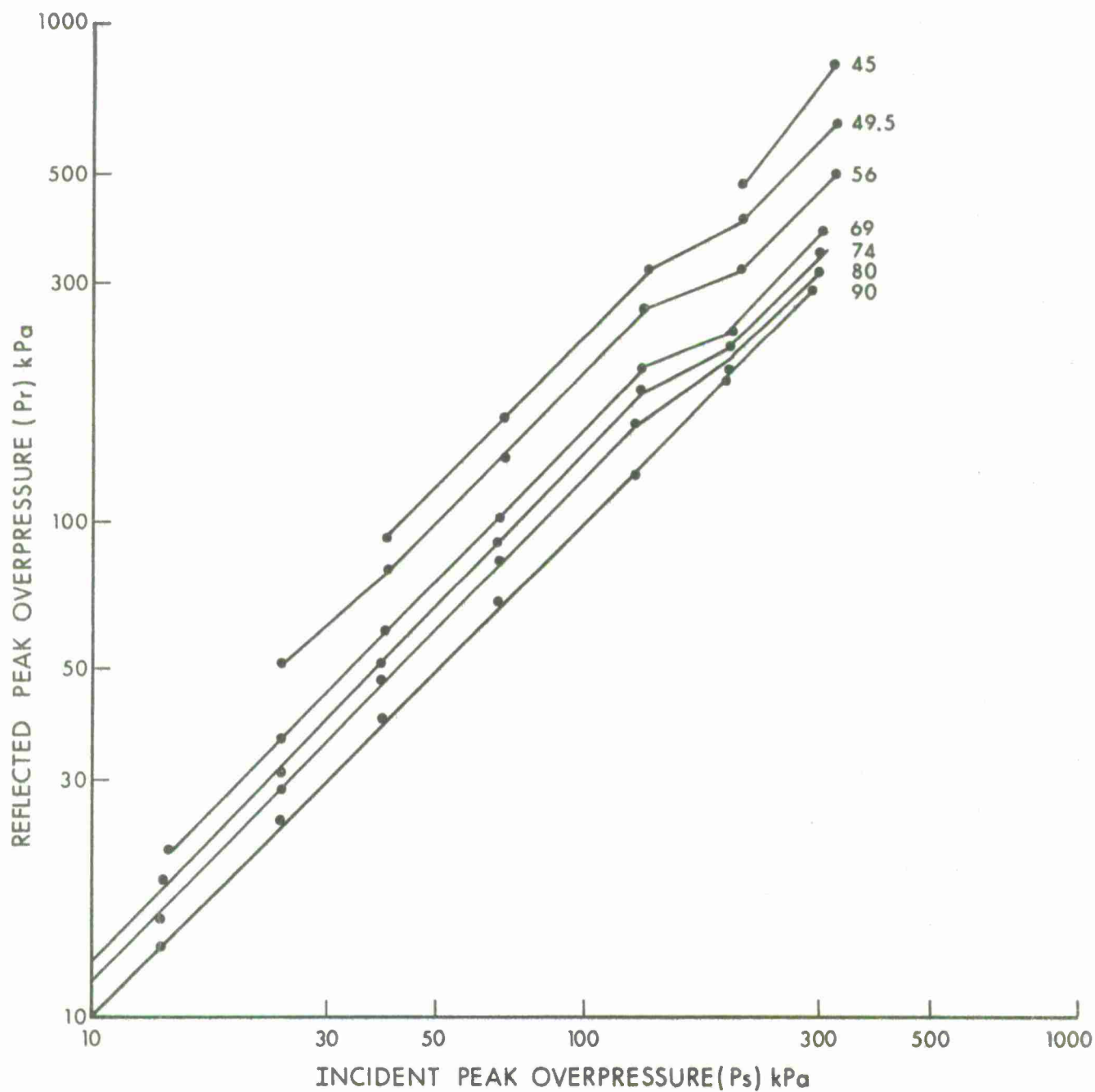


Figure 18. Reflected Pressure (P_r) versus Incident Pressure (P_s) in the Mach Reflection Region as a Function of Angle of Incidence.

The dashed line presented in Figure 19 is to show the difference in the zero degree or head-on reflected impulse on an infinite plane and that recorded on a finite model. The lower values recorded on the model are because the arrival of the rarefaction waves from the sides of the structure causes an increase in the rate of decay of the reflection pressure which produces a lower reflected impulse.

The reflected impulse recorded in the Mach reflection region is plotted in Figure 13 and presented in a different manner in Figure 20. In this figure the enhancement of reflected impulse becomes less as the angle of incidence approaches 90 degrees, or side-on conditions. The vortex from the front corner of the structure causes a lowering of the overpressure during the passage of the blast wave and the reflected impulse becomes less than the side-on impulse at an angle of incidence of 90 degrees. This is also true at some of the values measured at an 80 degree angle of incidence.

V. CONCLUSIONS

The results presented in this report are based on one size structure and one charge mass. Therefore it cannot be applied in general to all size structures and all charge masses. The model was 0.3048m x 0.3048m x 0.4572m exposed to a 1 kg charge mass. This means the results could be applied to structures where the size is increased by the cube root of the charge mass, for example, a 1000 kg charge mass and a 3.048 metre structure or a 125000 kg charge and a 15.24 metre structure or a 512000 kg charge mass and a 24.38 metre structure 36.58 metres high. Care would have to be exercised in applying the results to other combinations of charge mass and structure dimensions. If a charge mass is held constant and the structure size increased, the reflected impulse values in the regular reflection region would approach the infinite plane case.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the outstanding work of Mr. S. Dunbar, the electrical engineer in charge of the instrumentation facility, who was responsible for recording all of the overpressure versus time data. He also processed the analog magnetic data tape through the data conversion computers to produce the information in digital form for plotting and analysis.

The authors also wish to acknowledge the work of Mr. K. Holbrook, technician and explosive handler for the excellent job done in site preparation, blast line installation, and model instrumentation and placement.

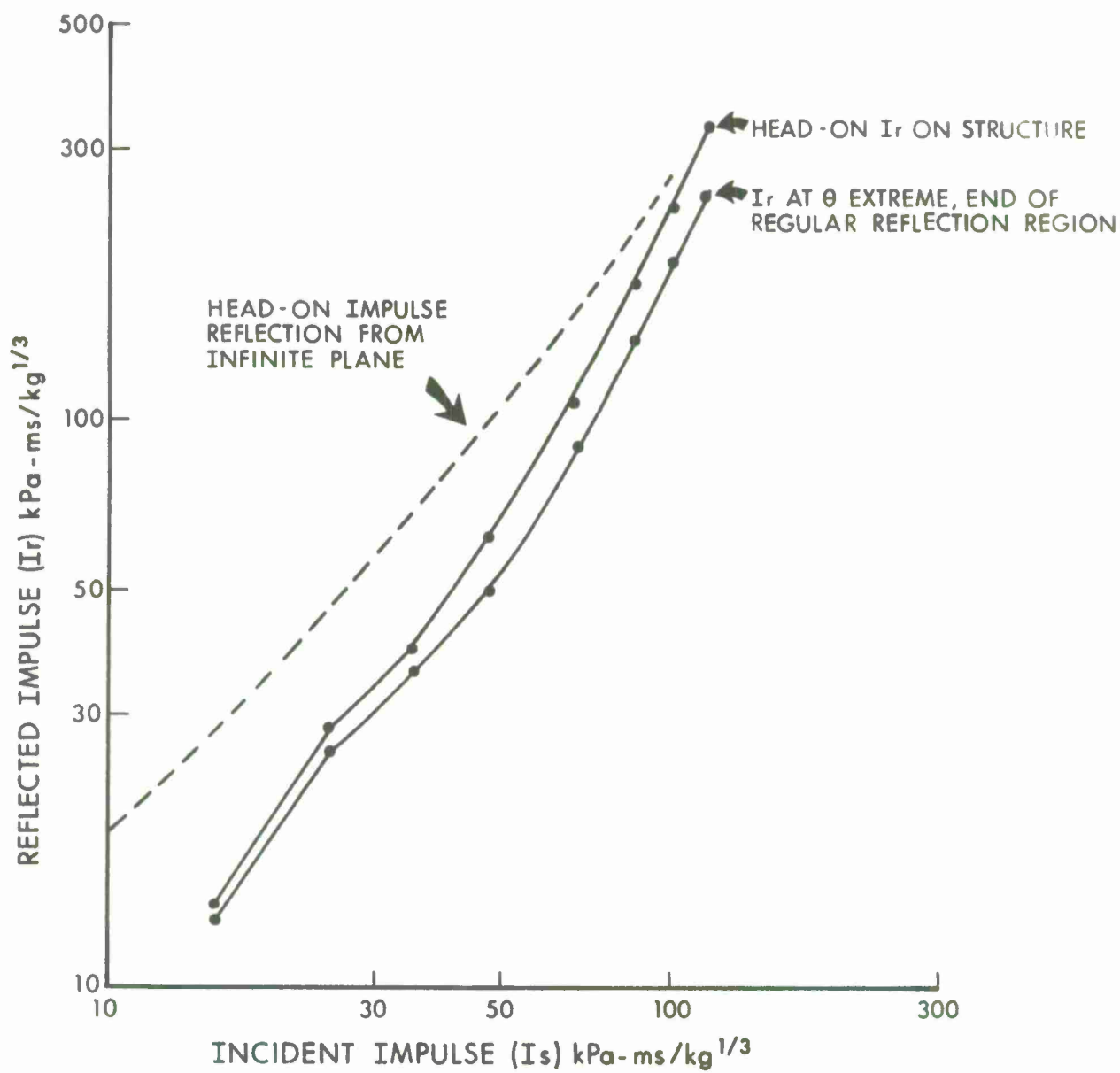


Figure 19. Scaled Reflected Impulse (I_r) versus Scaled Incident Impulse (I_s) in the Regular Reflection Region.

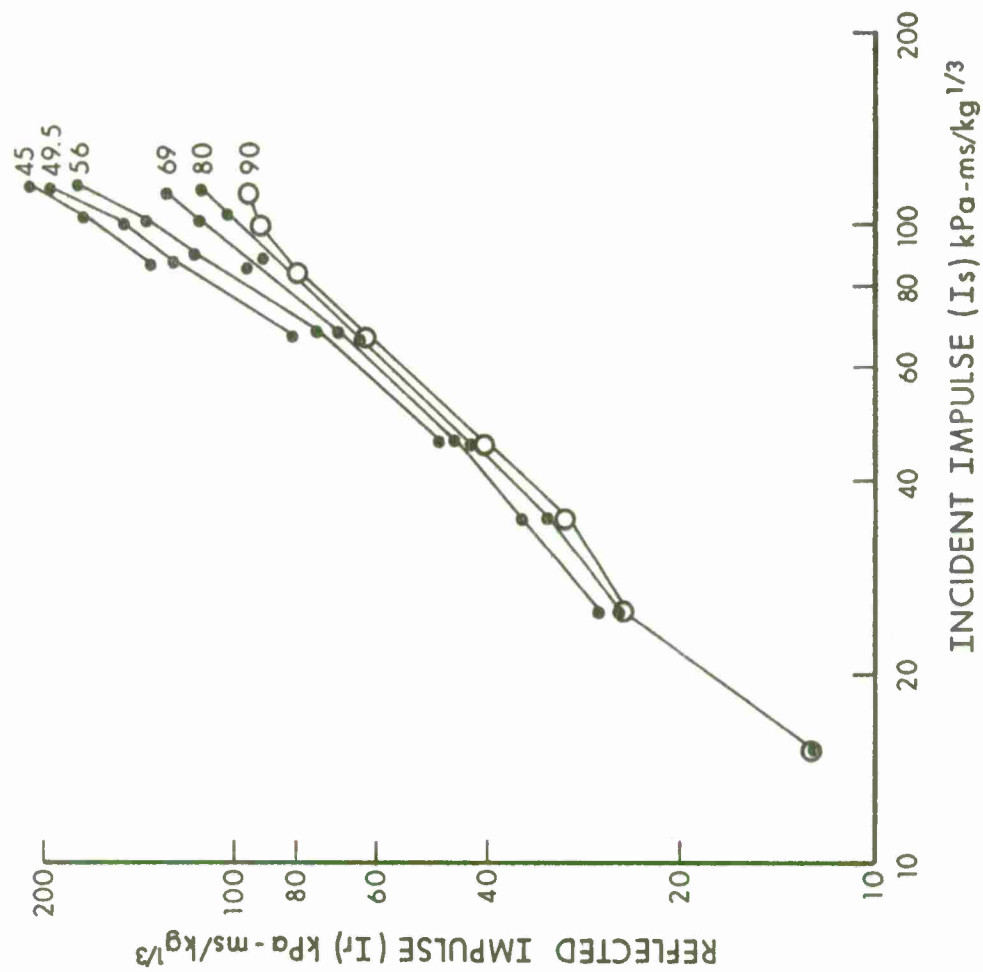


Figure 20. Scaled Reflected Impulse (I_r) versus Scaled Incident Impulse (I_s) in the Mach Reflection Region as a Function of Angle of Incidence.

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